

VIRTUAL ANTENNA TECHNOLOGY (VAT) AND APPLICATIONS

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VIRTUAL ANTENNA TECHNOLOGY (VAT) AND APPLICATIONS**CLAIM FOR PRIORITY**

5 This application claims priority to United States
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TECHNICAL FIELD OF THE INVENTION

10 [0001] The present invention is directed, in general, to
antenna arrays and applications and, more specifically, to
an antenna array including both physical and virtual
antennas as well as applications for such an antenna array.

BACKGROUND OF THE INVENTION

15 [0002] Traditional antenna arrays exhibit performance
related to the number of antenna elements. However, the
20 complexity and cost of such arrays also increases rapidly
as a function of the number of antenna elements. In
addition, various limitations render current antenna array
technology limited in application.

[0003] There is, therefore, a need in the art for improved antenna array technology, as well as improvements to various applications for antenna array technology.

SUMMARY OF THE INVENTION

[0004] To address the above-discussed deficiencies of the prior art, it is a primary object of the present invention to provide, for use in an antenna array system, derivation of the magnitude and phase of a relationship resulting from propagation delay between a sample taken at a first antenna to a sample taken at a second antenna at a different time to derive a data value for a virtual antenna. Sub-patch antennas perturbed in elevation are employed to expand the elevation range of acceptable gain. Multiple arrays each providing a separate radio frequency output are employed with digital beamform steering to a single point, together with low noise amplification at the feed point, to achieve sufficient gain with an acceptable total array size. A modular implementation with fiber transport is preferably used.

[0005] The foregoing has outlined rather broadly the features and technical advantages of the present invention so that those skilled in the art may better understand the detailed description of the invention that follows. Additional features and advantages of the invention will be described hereinafter that form the subject of the claims of the invention. Those skilled in the art will appreciate

that they may readily use the conception and the specific embodiment disclosed as a basis for modifying or designing other structures for carrying out the same purposes of the present invention. Those skilled in the art will also
5 realize that such equivalent constructions do not depart from the spirit and scope of the invention in its broadest form.

[0006] Before undertaking the DETAILED DESCRIPTION OF THE INVENTION below, it may be advantageous to set forth
10 definitions of certain words or phrases used throughout this patent document: the terms "include" and "comprise," as well as derivatives thereof, mean inclusion without limitation; the term "or" is inclusive, meaning and/or; the phrases "associated with" and "associated therewith," as
15 well as derivatives thereof, may mean to include, be included within, interconnect with, contain, be contained within, connect to or with, couple to or with, be communicable with, cooperate with, interleave, juxtapose, be proximate to, be bound to or with, have, have a property
20 of, or the like; and the term "controller" means any device, system or part thereof that controls at least one operation, whether such a device is implemented in hardware, firmware, software or some combination of at least two of the same. It should be noted that the

functionality associated with any particular controller may be centralized or distributed, whether locally or remotely. Definitions for certain words and phrases are provided throughout this patent document, and those of ordinary skill in the art will understand that such definitions apply in many, if not most, instances to prior as well as future uses of such defined words and phrases.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] For a more complete understanding of the present invention, and the advantages thereof, reference is now
5 made to the following descriptions taken in conjunction with the accompanying drawings, wherein like numbers designate like objects, and in which:

[0008] FIGURES 1A through 1F depict comparative diagrams of the structure and operation of a conventional antenna
10 array and an antenna array with virtual antennas according to various embodiments of the present invention;

[0009] FIGURES 2A through 2I illustrate an annular ring antenna structure according to one embodiment of the present invention; and

15 [0010] FIGURES 3A through 3C illustrate the structure and operation of an antenna array with perturbation of sub-patch element phases to compensate for pitch and roll according to one embodiment of the present invention;

20 [0011] FIGURES 4A and 4B depict modular, fiber transport antenna array system architectures for a beamformer according to one embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0012] FIGURES 1A through 4B, discussed below, and the various embodiments used to describe the principles of the present invention in this patent document are by way of illustration only and should not be construed in any way to limit the scope of the invention. Those skilled in the art will understand that the principles of the present invention may be implemented in any suitably arranged device.

[0013] FIGURES 1A through 1F depict comparative diagrams of the structure and operation of a conventional antenna array and an antenna array with virtual antennas according to various embodiments of the present invention. FIGURE 1A depicts a traditional "digital" linear antenna array system. Antenna array system 100 includes a plurality of M linearly-aligned antennas 101a-101m (where "M" and "m" are equal to each other and both equal to any positive integer greater than one). Each antenna 101a-101m receives a signal which is mixed with a common local oscillator (LO) signal at mixers 102a-102m. The outputs of mixers 102a-102m are passed through analog-to-digital (A/D) converters 103a-103m. A digital signal processor (DSP) 104 received signals from A/D converters 103a-103m.

[0014] Within antenna array system 100, a beamformed array gain G is achieved based on the number M of antenna elements:

$$G \sim 10 \log_{10}(M). \quad (1)$$

5 The half-power beam width (HPBW) resolution is given by:

$$HPBW \sim \frac{57^\circ}{M-1} \quad (2)$$

for sensors (antennas 101a-101m) spaced $\frac{1}{2}\lambda$, where λ is the wavelength of the desired or subject signal, giving an array size (including the ground plane) of $\frac{1}{2}\lambda \cdot M$. The array system 100 has M (theoretical) degrees of freedom, such that $M-1$ is the maximum number of intererers or jamming devices that may be handled by system 100.

[0015] FIGURE 1B illustrates operation for one embodiment of the traditional linear array antenna system. Antenna system 110 has three linearly-aligned antennas spaced apart by a distance d . For an incident plane wave $S(t)$ arriving at an angle θ with respect to an antenna reference direction, the baseband complex digital samples received at antennas 1-3 at times t_1 , t_2 and t_3 may be represented as: $x_1(t_1)$, $x_2(t_1)$, and $x_3(t_1)$; $x_1(t_2)$, $x_2(t_2)$, and $x_3(t_2)$; and $x_1(t_3)$, $x_2(t_3)$, and $x_3(t_3)$. The delay between portions of plane wave $S(t)$ arriving at different antennas is given by:

$$delay = \frac{d \cdot \sin \theta}{c} \quad (3)$$

where c is the velocity of wave propagation. The digital sample data may therefore be expressed as:

$$\begin{aligned} x_1(t_1) &= S(t_1)e^{-j\omega \cdot delay \cdot 2} + n_1(t_1) \\ x_2(t_1) &= S(t_1)e^{-j\omega \cdot delay \cdot 1} + n_2(t_1) , \\ x_3(t_1) &= S(t_1)e^{-j\omega(0)} + n_3(t_1) \end{aligned}$$

$$\begin{aligned} x_1(t_2) &= S(t_2)e^{-j\omega \cdot delay \cdot 2} + n_1(t_2) \\ x_2(t_2) &= S(t_2)e^{-j\omega \cdot delay \cdot 1} + n_2(t_2) \\ x_3(t_2) &= S(t_2)e^{-j\omega(0)} + n_3(t_2) \end{aligned}$$

and

$$\begin{aligned} x_1(t_3) &= S(t_3)e^{-j\omega \cdot delay \cdot 2} + n_1(t_3) \\ x_2(t_3) &= S(t_3)e^{-j\omega \cdot delay \cdot 1} + n_2(t_3) . \\ x_3(t_3) &= S(t_3)e^{-j\omega(0)} + n_3(t_3) \end{aligned}$$

[0016] FIGURE 1C illustrates operation of an antenna array including virtual sensors according to one embodiment of the present invention. Antenna system 120 includes only two antennas 1-2, with a third "virtual" antenna 3. By letting

$$x_1(t_2) \cdot K = x_2(t_1) \Rightarrow K = \frac{x_2(t_1)}{x_1(t_2)} , \quad (4)$$

a virtual sensor (antenna) x'_3 may be created by blind mapping

$$K \cdot x_2(t_2) = x'_3(t_1) \quad (5)$$

such that, for the noiseless case:

$$x'_3(t_1) = \frac{x_2(t_1)}{x_1(t_2)} \cdot x_2(t_2) . \quad (6)$$

The expression for $x'_3(t_1)$ may alternatively be written as:

$$\begin{aligned} x'_3(t_1) &= \left[\frac{S(t_1)e^{-j\omega \cdot \text{delay} \cdot 1}}{S(t_2)e^{-j\omega \cdot \text{delay} \cdot 2}} \right] S(t_2)e^{-j\omega \cdot \text{delay} \cdot 1} \\ &= \left[\frac{S(t_1) \cdot S(t_2)}{S(t_2)} \right] \cdot \frac{e^{-j\omega [\text{delay} \cdot 1 + \text{delay} \cdot 2]}}{e^{-j\omega \cdot \text{delay} \cdot 2}} , \\ &= S(t_1) \cdot e^{-j\omega(0)} \end{aligned} \quad (7)$$

which produces the actual signal value and correct phase
for $x'_3(t_1)$.

[0017] For the noisy case, the solution is more complex but ultimately arrives at:

$$x'_3(t_1) = S(t_1) \cdot e^{-j\omega(0)} + \text{noise_term} . \quad (8)$$

[0018] FIGURE 1D illustrates expansion of the antenna array to include a system 130 having physical antennas 1-3 and more than one virtual sensor 4-5. In this embodiment, two multiplier terms K_1 and K_2 are derived for use in generating data values for the virtual sensors. FIGURE 1E illustrates that the extension of the principle to either side of a physical antenna array, to further increase the number of virtual sensors within an antenna system 140.

[0019] An antenna array having an original aperture of M physical antennas and including P virtual sensors according

to the present invention will exhibit a beamformed array gain G of:

$$G \sim 10 \log_{10}[M + P \cdot (M - 1)] \quad (9)$$

as well as a highly improved resolution:

5

$$HPBW \sim \frac{57^\circ}{M + P \cdot (M - 1)} \quad (10)$$

The number of degrees of freedom is also increased, even though the physical array size is conserved or optionally reduced.

[0020] A number of application may exploit the use of
10 virtual sensors according to the present invention,
including: radio frequency (RF) and acoustic sensing
and/or direction finding (DF); digital radar; radio stellar
cartography; as anti-jamming for global positioning system
(GPS) systems; sonar line-of-bearing (LOB) systems; digital
15 beamforming in commercial services such as cellular or
Third Generation (3G) wireless communications, or real time
data networks; or as a broadcast receiver for satellite or
terrestrial digital broadcast systems (DBS), such as found
in mobile vehicles, where smaller, more aesthetic antenna
20 systems having no moving parts may be employed with self-
tracking and alignment to satellites. Use of the present
invention may improve the critical time on target parameter
for existing systems.

[0021] Use of virtual antennas as described above differs from synthetic aperture radar (SAR) and synthetic aperture sonar (SAS) in that no movement of the array is required. Instead, a coherent virtual sensor is achieved by "blind" mapping. In addition, the virtual antenna technology may be employed on real time signals. For these reasons, the present invention may also be employed to improve imaging systems such as SAR and SAS, and those employed in unmanned aerial vehicles (UAVs) employed for airborne reconnaissance.

[0022] The present invention obtains additional array aperture and resolution without adding (or requiring fewer) actual sensors. Virtual antennas may improve the resolution of existing arrays, and lower the system cost of new systems by requiring installation of fewer antennas. Unlike counter type devices, such as computed axial tomography (CAT) systems), the present invention provides both phase and amplitude.

[0023] Virtual antennas may be employed for applications using an integration approach to resolving raw data, such as auto-correlations and cross-correlations. In such application the correlation noise and cross-signal terms either tend to zero or are constant. In non-integrated, sample-by-sample applications, such as real time signaling,

correlation noise and cross-signaling should be addressed. This is possible since the non-exponential distinguishing factor terms $n_1(t)$, $n_2(t)$ and $n_3(t)$ are not, in fact, independent.

5 [0024] FIGURE 1F illustrates an antenna array system employing virtual antennas according to one embodiment of the present invention. Antenna system 150 may be implemented by insertion of a virtual antenna technology application specific integrated circuit (ASIC) 151
10 performing the computations described above between the A/D converters 103a-103c and the digital signal processor 104 of a traditional antenna array system.

[0025] FIGURES 2A through 2I illustrate an annular ring antenna structure according to one embodiment of the
15 present invention. The annular ring antenna structure of this embodiment may be used in conjunction with the virtual antenna technology described above, or independently.

[0026] FIGURE 2A depicts a patch antenna 200. Patch antennas typically include a copper patch 201 of
20 approximately $\frac{1}{2}$ inch by $\frac{1}{2}$ inch on a printed circuit board (PCB) material 202, such as FR4 or G10. The antenna 200 exhibits a half-hemisphere radiation pattern with 4 decibel gain with reference to an isotropic radiator (dBi) at 30° and 7 dBi at 90° . Antenna 200 is flat or conformal and

provides near half-hemisphere coverage, with roughly +4 to +7 dBi boresight gain. This structure is suitable for frequencies under 5 gigaHertz (GHz), but exhibits unacceptable losses for frequencies greater than 5 GHz, requiring use of low noise amplifiers to overcome losses.

[0027] The simple patch antenna structure 200, when mounted on the top of a wing or the fuselage for an aircraft as shown in FIGURE 2B, provides about +4 to +7 dBi gain in directions at which a satellite signal may be received during flight, which is too low to support high speed data and/or satellite (television) video. Thus, while providing full half-hemisphere coverage in a simple, inexpensive manner, the simple patch antenna is unsuitable for transmission in the Ku-band.

[0028] FIGURE 2C illustrates a patch antenna array, in which a plurality of patch antennas are arranged in rows and columns. The increase in effective area produces an increase in antenna gain, making the patch antenna array a cost effective method to improve antenna area and gain. The signals from the individual antenna elements within the array are summed in phase. For a nine element patch antenna array as illustrated, this increases maximum gain by $10\log(9) = 9.5$ dBi, achieving a boresight gain of 7 dBi

+ 9.5 dBi = 16.5 dBi and a gain at thirty degrees of 4 dBi
+ 9.5 dBi = 13.5 dBi.

[0029] However, summing the signals in phase produces a
single, narrow, fixed beam projected straight up from the
array, which is unlikely to be the direction of a satellite
relative to an aircraft, as shown in FIGURE 2D. Thus,
while the patch antenna array is simple and inexpensive and
produces higher gain, the gain is not steered to
satellites, and is still too low to support high speed data
and/or satellite video. Gain on the order of +30 to +34
dBi is required to support high speed data and satellite
television for higher end aircraft.

[0030] Beam steering required for high gain may be
achieved by mechanical means, RF phasing of the array, or
digital phasing of the array (digital beamforming). The
mechanical approach, while inexpensive, suffers from poor
reliability and requires a significant radome size, causing
significant aerodynamic drag for small aircraft and highly
increasing structural loading and Federal Aviation
Administration (FAA) certification costs. Use of an RF
phased array produces a flat profile with low drag, but is
extremely expensive due to the high cost of phase shifters.

[0031] Use of a digital phase array (digital
beamforming) to steer a patch antenna array produces a flat

profile with low drag, uses low cost DBS RF components and DSP components having costs that are quickly and steadily becoming considerably lower, and provides a large range of added features.

5 [0032] Using a 3X3 annular ring patch antenna array illustrated in FIGURE 2C with a total array size of approximately 3 inches by 3 inches, a gain of about +13.5 dBi on a fixed beam within the 30° to 50° elevation range necessary for DirecTV and EchoStar from a purely passive
10 design. However, that gain is insufficient for television or data, since satellite dishes produce + 34 dBi gain. The need for additional gain requires steering, but the annular ring structure reduces DBF complexity and costs.

[0033] FIGURE 2E depicts an annular ring patch antenna
15 array according to one embodiment of the present invention. Four rows and four columns of 3X3 sub-arrays, having a total size of approximately 12 inches by 12 inches, are combined appropriately to achieve a passive gain improvement of $10\log(16) = 12$ dBi. Steering of the 16
20 beams is still required. In the present invention, each antenna sub-array element generates its own annular ring radiation pattern with 13.5 dBi gain, so that there are 16 annular rings (patterns), and is connected to a separate RF output as shown in FIGURE 2E. Using beamforming, the beam

within an annular ring may be "phased" to point to a particular location in space, as illustrated in FIGURE 2F. Each individual antenna patch sub-array is beamformed summed to the same point in space as shown in FIGURE 2G, producing constructive interference.

[0034] Use of an annular ring passive antenna structure steered to particular satellites in the sky, assumed to be located between particular elevation angles from a horizontally positioned flat panel when the antenna array is located anywhere across a geographic region of coverage (e.g., the continental United States), combined with a multi-element digital beamformer reduces the number of DBF elements required by a factor of 9 to 16 times, with a corresponding reduction in cost.

[0035] Assuming that a 3X3 sub-array generates approximately 13.5 to 15 dBi gain towards the satellite between a 30° and 50° elevation angle, beamform summing the sub-arrays to the same point simply adds their power together, so that 16 sub-arrays produce a gain of $10\log(16) = 12$ dBi with an effective total antenna gain of 13.5 dBi + 12 dBi = 25.5 dBi or 15 dBi + 12 dBi = 27 dBi.

[0036] An additional 2-3 dBi of gain should be possible using low noise amplifiers (LNAs) at the RF feed points to a downconverter, significantly improving aperture

efficiency so that a 9 inch by 9 inch 16X16 array should generate, between 30° and 50° elevation, roughly 26 to 30 dBi at broadside and roughly 25 to 28 dBi at 30 degrees elevation. Since satellite dishes have +34 dBi gain, and
5 additional 9 to 6 dB is needed. By increasing the overall array size of the 16X16 array to 18 inches by 18 inches, with LNAs directly at the feed points, +34 dBi gain should be generated.

[0037] FIGURES 2H and 2I illustrate different configurations of a beamformed steered patch antenna array system according to the present invention. Each includes an antenna array 203 of the type described above coupled to a downconverter block 204 (including LNAs at the feed points). The downconverter 204 is connected to a digital
10 signal processor block 205 either directly as illustrated in FIGURE 2H or by cables as illustrated in FIGURE 2I. The digital signal processor block 205 is connected by cables to a monitor or display computer 206.
15

[0038] Many different passive antenna types and
20 configurations will produce an annular ring radiation pattern, such as a combination of horizontal patch elements or a combination of vertical dipoles. Conventional digital beamforming methodologies apply or require a transmit/receive module or blocks for each patch element to

allow beamforming (generation) of a beam in any direction within the half-hemisphere. Thus, for example, the system of FIGURE 3E would require $3 \times 3 \times 4 \times 4 = 144$ transmit/receive modules, or more. However, for most satellite applications, the direction (beam) to the satellite is between a fixed range in the elevation plane, so that sub-element arrays can be used to generate the beams (M element sub-array), reducing the number of effective array elements by M and correspondingly reducing the number of required digital beamforming transmit/receive modules by M.

[0039] The present invention uses known and fixed geosatellite positions and an annular ring antenna structure to reduce the complexity, number of components, and cost of a digital beamformer for moving platforms.

[0040] FIGURES 3A through 3C illustrate the structure and operation of an antenna array with perturbation of sub-patch element phases to compensate for pitch and roll according to one embodiment of the present invention. Perturbation of sub-patch elements as described in connection with these figures is an optional modification of the invention depicted and described above in connection with FIGURES 2E through 2I, and may optionally be utilized in conjunction with the virtual antenna technology described above, or independently.

[0041] FIGURE 3A illustrates an antenna array with a plurality of sub-patch arrays 1-16 arranged in rows and columns. Each individual sub-patch array 1-16 has an annular ring and is perturbed in elevation angle to have a different elevation angle center, such as 40°, 45°, 35° and 40° for sub-patch arrays 1-4 as illustrated in FIGURE 3B. A digital beamformer then sums the signals from the antennas to the optimal elevation angle, to increase the elevation angle range from, for example, 30°-50° to 15°-60°. In this manner, significant increase in allowable platform pitch and roll may be achieved with extremely high speed adaptation of the array.

[0042] FIGURES 4A and 4B depict modular, fiber transport antenna array system architectures for a beamformer according to one embodiment of the present invention. The architectures depicted and described may be employed in conjunction with any or all of the virtual array technology, the annular ring antenna technology, and/or the perturbation of sub-patch element phases to compensate for pitch and roll as described above, or independently.

[0043] In the embodiment illustrated in FIGURE 4A, antenna elements, filters/LNAs, block converters (to the intermediate frequency) and fiber converters are implemented in one module. That module is coupled by a

fiber cable and DC power cable to a separate module within the platform also including fiber converters together with a DSP. Keeping the antenna array size small requires high antenna efficiency and low transmission line losses out of each sub-element to the sub-branched point (trunk). In the present invention, this need is addressed by including an LNA directly at the element feed to overcome the subsequent transmission line losses. However, it may NOT be desirable to have the DSP at the antenna, in order to provide flexibility in the features to be added or changed, which would be difficult if the DSP were located at the antenna (platform exterior) location. Transporting microwave signals on a cable is undesirable due to high losses and the expense. On the other hand, tuning with the DSP and IF conversion with A/Ds are both desirable. Thus, use of fiber cables, which are easy to route, when the DSP is not at the antenna location requires analog transport over fiber rather than digital signals. The A/Ds may thus be moved to the other end of the fiber cable as shown in FIGURE 4B.

[0044] Although the present invention has been described in detail, those skilled in the art will understand that various changes, substitutions, variations, enhancements, nuances, gradations, lesser forms, alterations, revisions,

improvements and knock-offs of the invention disclosed herein may be made without departing from the spirit and scope of the invention in its broadest form.